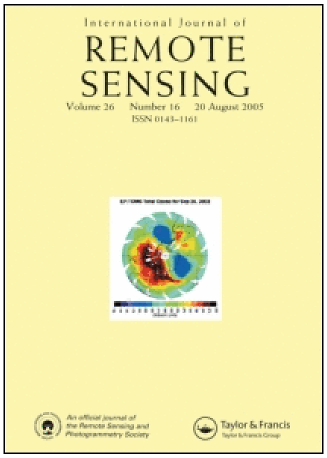

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Global cloud top height and thermodynamic phase distributions as obtained by SCIAMACHY on ENVISAT

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Global cloud top height spatial distribution as obtained using highly spectrally resolved (≈0.42 nm) SCIAMACHY on ENVISAT measurements in the oxygen A-band is presented. Also the global cloud phase index map is given. The results were derived using semi-analytical cloud retrieval algorithms developed by the authors specifically for SCIAMACHY cloud retrievals. The algorithm is applicable for clouds having an optical thickness larger than 5. Therefore, only thick cloud fields were selected for this study. We found that the global average cloud top height is close to 6 km and the most frequent value of the phase index is close to 0.8.

1. Introduction

The information on the vertical distribution of liquid and solid (ice) water in the terrestrial atmosphere (e.g. the position of cloud layers) is very important for a number of applications including climate studies, atmospheric thermodynamics and dynamics, numerical weather prediction, atmospheric heating rate calculations, and trace gas retrievals, to name a few. The capability of passive sensors is very limited in this respect because they mostly sense the upper boundary of cloud systems. This is especially true for infrared (IR) and thermal imagery. Measurements in ultraviolet (UV) and visible (e.g. outside of gaseous absorption bands) give vertically integrated quantities and provide no clue on vertical distributions of cloud parameters. Therefore, the cloud research community needs specially designed active spaceborne sensors specifically designed for cloud three-dimensional (3D) profiling (see, e.g. the paper devoted to CloudSat by Stephens *et al.* (2002)). This by no means leads to the rejection of information on clouds as obtained from passive satellite sensors. They can supplement active measurements both in space and time domains (especially as far as cloud top properties are concerned).

This paper is devoted to the analysis of one-year (2004) data as obtained by the SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY) onboard Environmental Satellite (ENVISAT) with respect to the cloud top height and cloud thermodynamic phase determination. This advanced optical instrument having approximately 8000 spectral channels in the spectral range 214–2380 nm is designed to measure stratospheric and tropospheric abundances of various trace gases including O_3, CH_4, NO_2, and SO_2, to name a few (Bovensmann *et al.* 1999). The information on cloud altitude as well as on cloud

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albedo and cloud fraction is of vital importance for correct retrievals of trace gas concentrations from space using SCIAMACHY.

A special Semi-Analytical CloUd Retrieval Algorithm (SACURA) has been developed and applied to SCIAMACHY spectral measurements with respect to the determination of cloud parameters from space. The fundamental theory behind the algorithm is fully described by Rozanov and Kokhanovsky (2004). The validation using thermal IR satellite measurements was performed by Rozanov *et al.* (2004, 2006) and Kokhanovsky *et al.* (2006a, 2007a).

2. Methodology

2.1 *SCIAMACHY*

The SCIAMACHY instrument is a passive remote sensing moderate resolution imaging spectrometer launched on 1 March 2002. SCIAMACHY is currently in operation on ENVISAT. It comprises a mirror system, a telescope, a spectrometer, and electronic and thermal sub-systems. Top-of-atmosphere (TOA) reflectance spectra are recorded simultaneously from 214 nm to 1750 nm, and in two smaller windows, 1940–2040 nm and 2265–2380 nm. Two diffuser plates are mounted on the backside of the elevation and azimuth mirrors to facilitate the direct solar light observations. Therefore, the instrument is capable of providing the normalized TOA reflection function $R=\pi I_r/\mu_0 E_0$, where I_r is the reflected light intensity, μ_0 is the cosine of solar angle, and E_0 is the solar light irradiance on the diffuser plate. The spatial resolution of SCIAMACHY depends on the spectral band. It is $30 \times 60\,\mathrm{km}^2$ for applications considered in this work. Measurements are performed at 10 a.m. equator passing local time.

SCIAMACHY also contains polarization measurement devices that have a spatial resolution of $30 \times 7\,\mathrm{km}^2$. This allows estimating a cloud fraction in the large field of view of the instrument. Such a coarse spatial resolution is needed to enhance the sensitivity of the instrument for the detection of trace gas abundances from space observations. This resolution makes an instrument not very suitable for aerosol and cloud research (e.g. due to possible broken cloud conditions in the field of view of the instrument). However, for extended cloud fields and cases with known cloud fractions (e.g. obtained by using enhanced spatial resolution broad band polarization measurement devices), SCIAMACHY provides useful information on cloud parameters. In particular, cloud top height (CTH) can be obtained by using highly spectrally resolved measurements in oxygen A-band (758–776 nm). Moreover, correspondent CTH is obtained on the spatial scale, which is usually used in climate models. Therefore, subsequent averaging of highly spatial resolved data is not required.

2.2 *SACURA*

The physical principle behind the cloud retrieval algorithm is quite simple. Indeed, the oxygen concentration is larger in lower atmospheric layers. Therefore, the oxygen spectral absorption band as detected on the satellite will have different depths depending on the cloud altitude. In particular, high clouds will screen oxygen producing shallow absorption lines in reflectance spectra. The main idea is to fit measured and calculated reflectance spectra in the spectral band 758–776 nm (spectral resolution 0.42 nm) with respect to cloud optical and geometrical parameters. The technique is described by Rozanov and Kokhanovsky (2004).

The result of this fit is the cloud geometrical thickness, cloud optical thickness, and cloud top height. All retrievals are performed assuming a vertically homogeneous cloud field with a given size distribution of spherical water droplets. Note that the O_2 A-band spectra are only weakly sensitive to the water cloud microstructure. Rozanov and Kokhanovsky (2004) studied the errors of retrievals that occurred because of *a priori* assumptions on the thermodynamic state of clouds and also on the type of liquid water profile inside of clouds. Quite large theoretical errors can occurr, if wrong profiles, number of cloud layers, and cloud thermodynamic state are used (up to 2.5 km). Retrievals for broken cloud fields are performed in the framework of independent pixel approximation (IPA) as described by Rozanov *et al.* (2006). For this, the reflection function of a broken cloud field is represented as a linear mixture of cloudy and clear portions of sky with values of linear mixture coefficients derived from the analysis of SCIAMACHY polarization measurement devices as explained by Rozanov *et al.* (2006). The errors of IPA for the determination of CTH using oxygen A-band spectrometry have been estimated by Kokhanovsky *et al.* (2006b) to be below 1.5 km, depending on the cloud fraction, the solar zenith angle, and the cloud geometrical thickness. This estimate was obtained by running a full 3D radiative transfer code in the O_2 A-band.

The validation of the retrievals using thermal IR measurements is given by Rozanov *et al.* (2004), who demonstrated that CTH as retrieved by SACURA for completely cloudy pixels is inside error bars (± 1 km) of results obtained using thermal imagery. A characteristic example of comparisons is given in figure 1 for the case of Global Ozone Monitoring (GOME) instrument (Burrows *et al.* 1999). In addition to SACURA, also retrievals using the Fast Retrieval Scheme for Clouds (FRESCO) (Koelemeijer *et al.* 2001) and Retrieval of Cloud Information using Neural Networks (ROCINN) (Loyola and Ruppert 1998, Loyola 2004) are shown. It follows that SACURA results based on O_2 A-band GOME measurements highly correlate with those obtained using ATSR-2 thermal IR measurements. Therefore, we are quite confident in the results obtained using SACURA for GOME. The validation of SACURA for SCIAMACHY is an ongoing process. The first results show that the performance of SACURA for SCIAMACHY is similar to that for GOME. In particular, Kokhanovsky *et al.* (2006a) found, using data of airborne lidar, that SACURA as applied to SCIAMACHY gives values of CTH with the error smaller than 1 km with overestimation of CTH by SACURA. The comparison with MODIS for a single scene gave 0.5 km overestimation of CTH by SACURA as compared to MODIS IR retrievals (Kokhanovsky *et al.* 2007a).

In addition to CTH retrievals, the phase index $v=R(1555\,\text{nm})/R(1670\,\text{nm})$ is studied, which serves as an indication of thermodynamic state of a cloud (Acarreta *et al.* 2004). This is due to different absorption and, therefore, reflectance of liquid water and ice at wavelengths 1555 and 1670 nm. Kokhanovsky *et al.* (2006b) found using theoretical calculations and also measurements that the value of v is generally smaller than 0.7 for ice clouds due to larger changes in reflectance for ice clouds as compared to water clouds at the pair of wavelengths specified above.

3. Results

Results of cloud top height retrievals using one year of SCIAMACHY O_2 A-band spectrometry are shown in figure 2. Data files with our retrievals for the years 2002–2007 are available at www.iup.physik.uni-bremen.de/sacura.

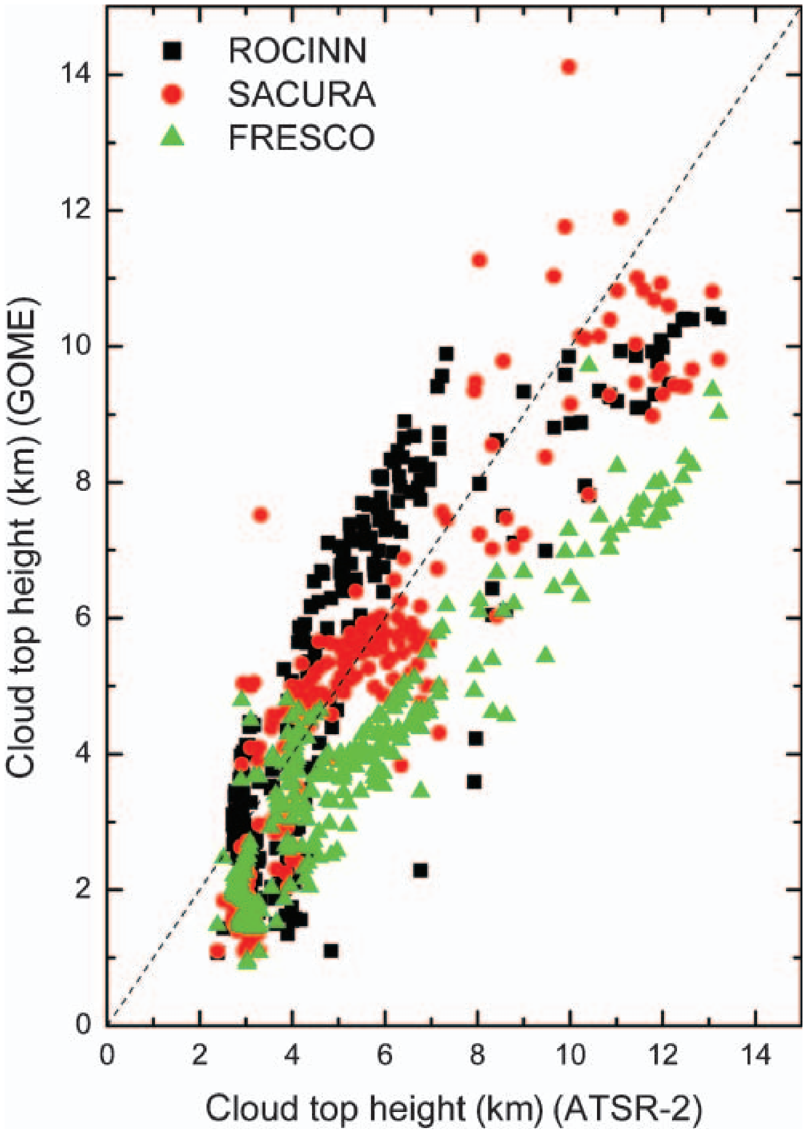


Figure 1. Comparison of cloud top heights retrieved using different algorithms based on GOME oxygen A-band data with those obtained from thermal infrared (IR) retrievals using Along Track Scanning Radiometer (ATSR-2) measurements for ERS-2 orbit 18223 on 15 October 1998. Only completely cloudy pixels are considered.

The global map obtained using O_2 A-band spectroscopy of terrestrial atmosphere (see figure 2) confirms main findings and facts related to the average atmospheric state of our planet as far as clouds are concerned, i.e. (i) the existence of high clouds in the equatorial region (so called Inter-Tropical Convergence Zone (ITCZ)). It is interesting that the belt of high clouds is narrower in the central Atlantic Ocean region and also in the Eastern Pacific. Clouds are much higher (and, therefore, also thicker) in the Western Pacific and also over the Indian Ocean; (ii) clouds are very low or not existent over deserts (e.g. Sahara). Also, three oceanic deserts with very small cloud activity are clearly seen on the map. They are situated west of Australia,

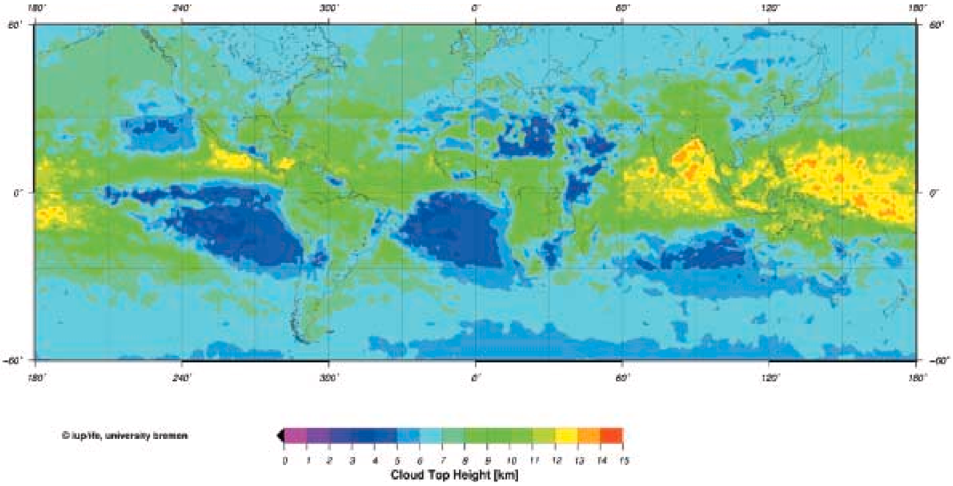


Figure 2. Distribution of cloud top heights as obtained from SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY) data using SACURA ($0.5^{\circ} \times 0.5^{\circ}$ grid). Cloud Top Height from SACURA (01-Jan-2004–31-Dec-2004).

west of South Africa, and west of South America. Generally, temperature of water is lower in oceanic deserts due to cold currents from the Antarctica region. This also leads to the suppression of evaporation and clouds. It is expected that the probability of rain in these oceanic regions must be very low as compared to, for example, ITCZ and the Western Pacific region (see figure 2); (iii) clouds over Nothern America and Eurasia are generally lower as compared to ITCZ. This is due to the general decrease of the tropopause altitude for lower latitudes.

The retrieved cloud top heights (see figure 2) correlate with the thermodynamic phase index retrievals shown in figure 3. In particular, the blue colour in figure 3

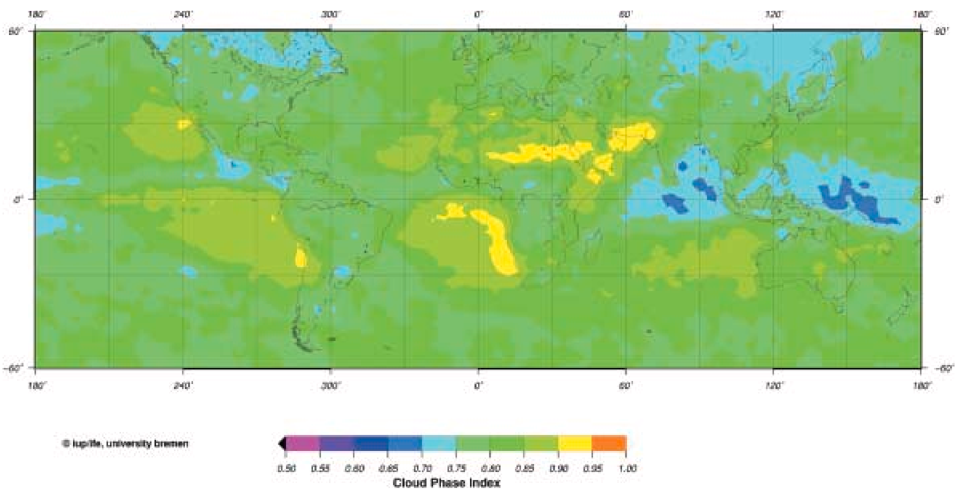


Figure 3. Global distribution of cloud phase index as obtained from SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY) data using SACURA ($0.5^{\circ} \times 0.5^{\circ}$ grid). Values of the phase index smaller than 0.7 correspond to ice clouds. Cloud Phase Index from SACURA (01-Jan-2004–31-Dec-2004).

corresponds to ice (either as a cloud or as snow; see parts of Canada and Russia on the map). This confirms the consistency of the cloud top altitude and cloud phase retrievals using SACURA. Indeed, the phase index v is lower (blue colour, $v \sim 0.7$) in areas, where high and, therefore, crystalline clouds are detected.

An interesting point is that after one year of data averaging, coherent features and structures as derived from measurements at different spectral regions (e.g. in 758–776 nm O_2 A-band (see figure 2), 1550–1670 nm near IR spectral range (see figure 3) and also in thermal IR (see the corresponding maps at MODIS' website http://modis.gsfc.nasa.gov) survive. These features, although with some minor changes, are preserved from year to year (see maps of CTHs given at the ISSCP website http://isccp.giss.nasa.gov) indicating the stability of cloud and therefore the climate system on our planet. Any appreciable change of this general pattern will lead to unpredictable events related to the change in the operation of the planetary machine driven mostly by the water cycle and related dynamic and thermodynamic processes. Therefore, the monitoring of processes as shown in figure 2 must be continued in future.

The global annual frequency distributions of CTH and phase index are given in figure 4(*a*) and 4(*b*), respectively. We found that the global average CTH is equal to 6 km (standard deviation (SD): σ=2.14 km) and the average phase index is equal to 0.8 (SD: σ=0.07). Of particular interest will be to compare the distribution given in figure 4 with the corresponding results obtained using other passive and active spaceborne sensors.

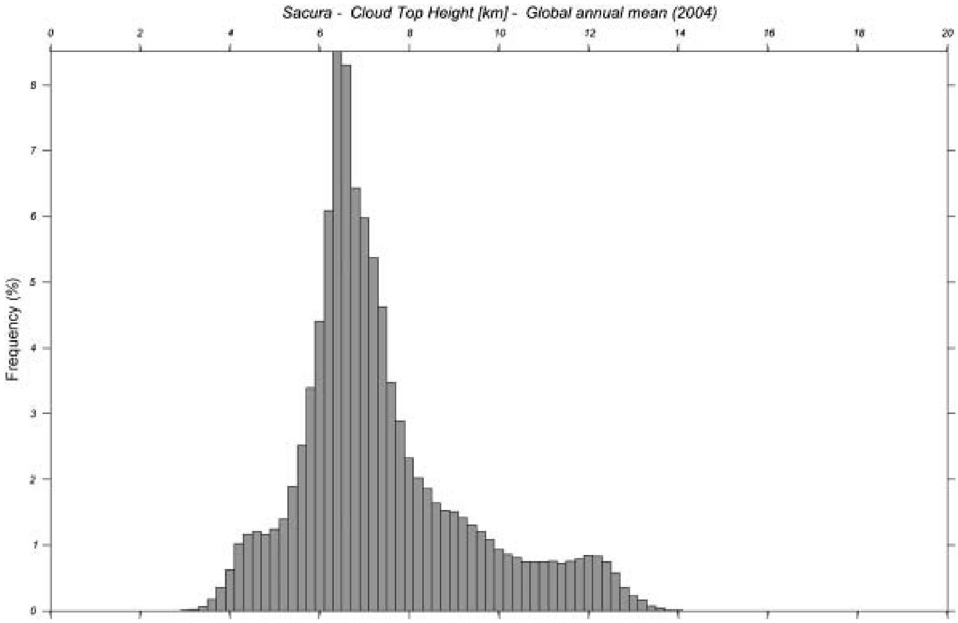
Distributions of derived cloud top heights as functions of the month for three latitudinal belts and also separately for Europe are shown in figure 5. It follows that CTHs are generally higher during the northern summer in both southern (around May) and northern (around August) belts. Cloud top heights for Europe do not considerably differ from the results for the whole belt 30–60° N. In the case of the tropical belt the highest clouds are observed during spring (close to 10 km height). The statistical distribution of CTHs is broadest for the tropical belt as follows from figure 5. The SDs are in the range of 3–4 km.

The SDs of the CTH probability distribution are smaller for southern and northern belts as compared to the tropical band of the order of 1 km for the southern belt and 2 km for the northern belt. Therefore, we conclude that the cloud variability in the southern hemisphere is lower compared to the variability of clouds in the northern hemisphere. An important factor of this difference is the different distribution of land and water surfaces in both hemispheres.

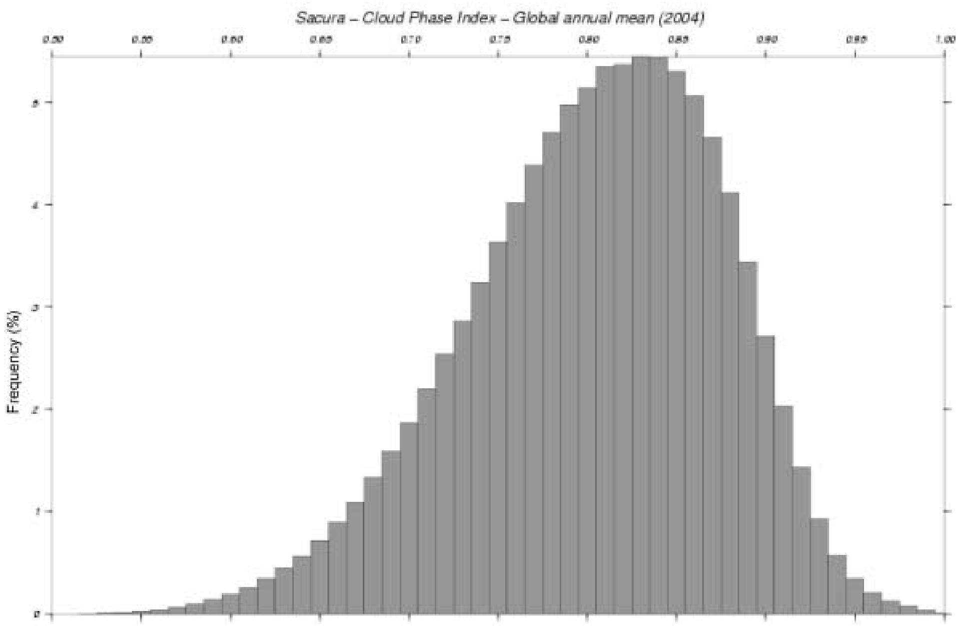
4. Conclusions

The analysis of the 2004 SCIAMACHY data allowed us to reach important conclusions related to the distribution of cloud liquid and ice water in the terrestrial atmosphere. We found that tops of optically thick clouds most frequently occur at 6 km height. This finding must be confirmed by independent measurements (preferably using active spaceborne sensors). The obtained results are valid for optically thick clouds. The analysis of thin clouds (e.g. Cirrus) is well beyond the framework of this work.

Our results also show the capability of SCIAMACHY to derive cloud properties from space. Corresponding retrievals on a day-to-day basis are available from www.iup.physik.uni-bremen.de/sacura.



(*a*)



(*b*)

Figure 4. Frequency distributions of (*a*) global cloud top height (SCIA-pixels involved: 6226561, mean: 5.97256 (median: 5.85883), s: 2.1401) and (*b*) the global phase index for the year 2004 (SCIA-pixels involved: 1554078, mean: 0.803586 (median: 0.809934), σ: 0.0712114).

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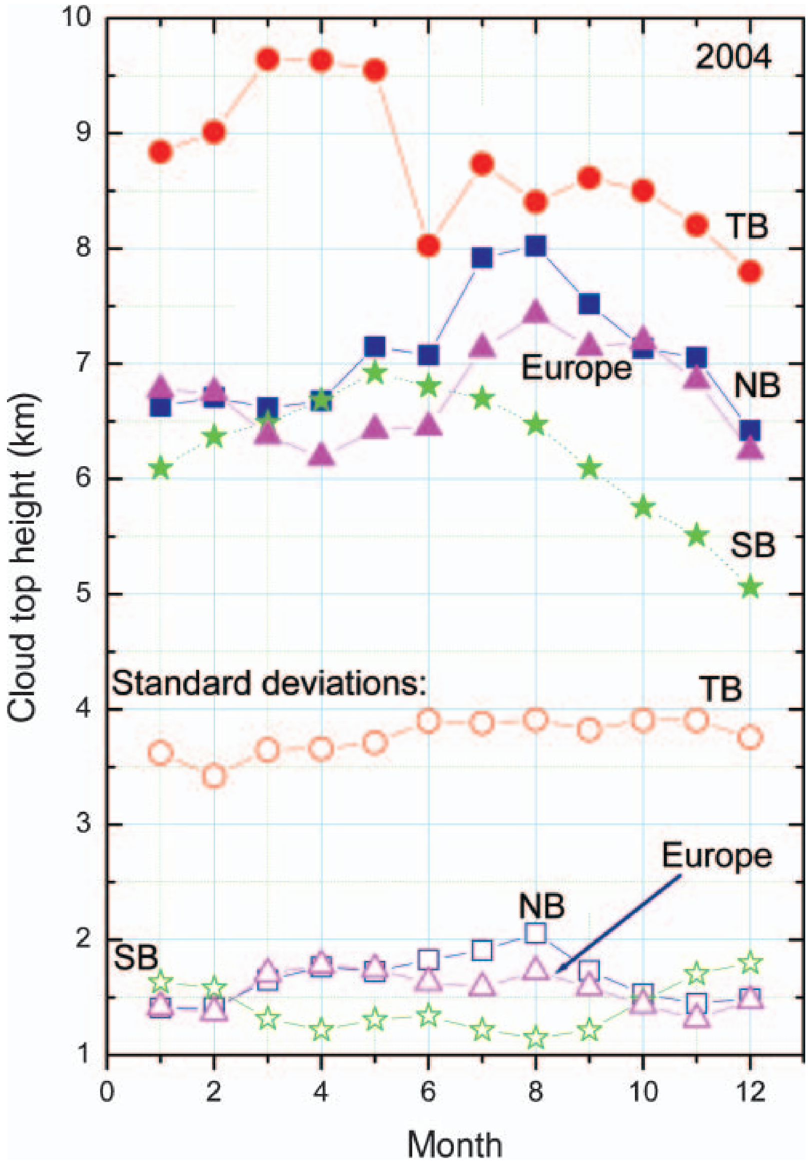

Figure 5. Curves with filled symbols give averaged distributions of cloud top height for the latitude interval [30° S, 30° N] (tropical belt (TB)), [30° S, 60° S] (southern belt (SB)), [30° N, 60° N] (northern belt (NB)), and the region of Europe. Curves with open symbols show standard deviations of corresponding CTH distributions.

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